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US Army Corps of Engineers
Waterways Experiment Station

Tri-Service Site Characterization and Analysis Penetrometer System Program

Cone Penetrometer Grouting Evaluation

by Landris T. Lee, Jr.

Approved For Public Release; Distribution Is Unlimited

Prepared for U.S. Army Environmental Center

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Final report

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Prepared for U.S. Army Environmental Center
Environmental Technology Division
Edgewood Arsenal
Edgewood, MD 21040

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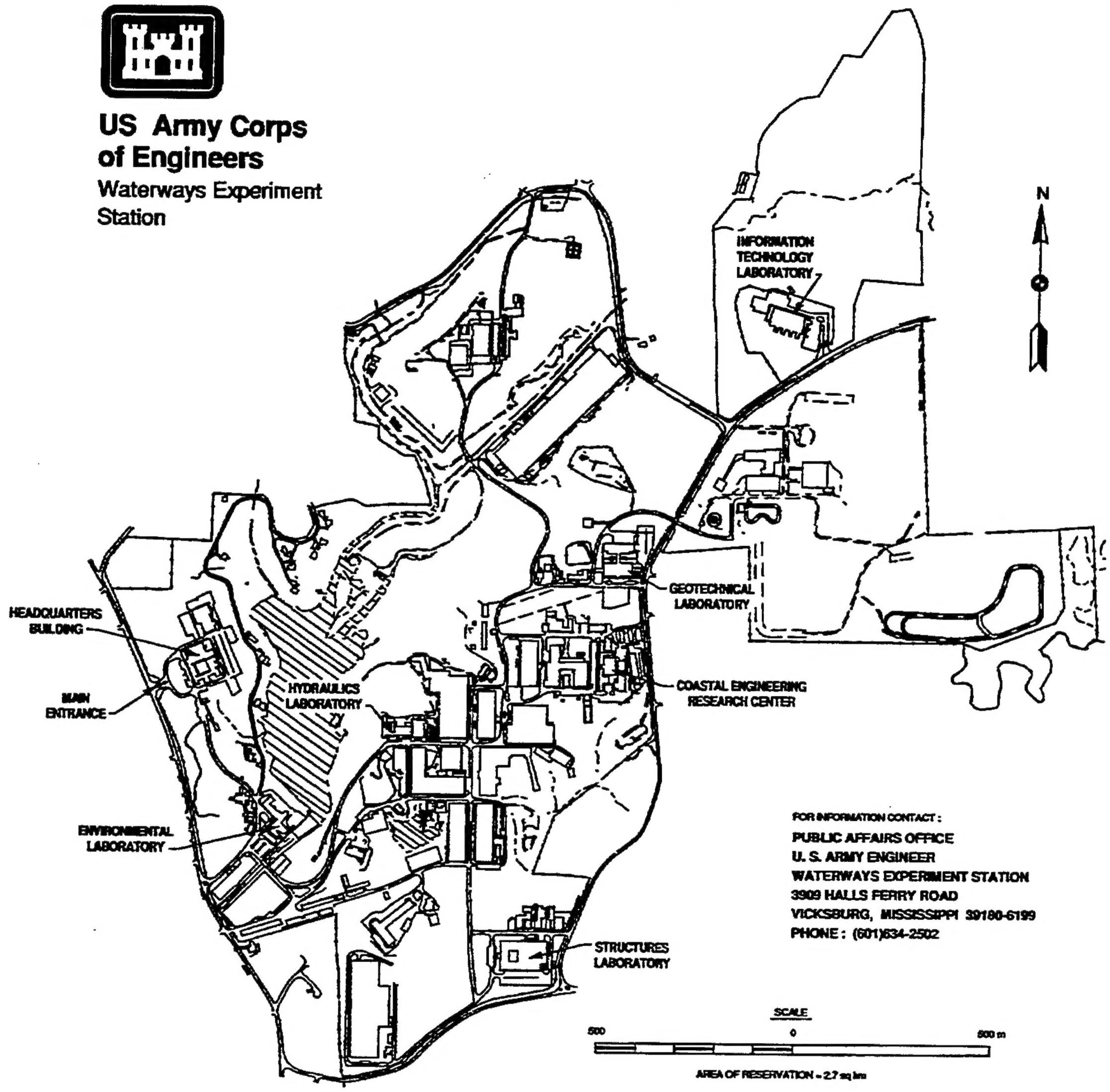

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Preface

The U.S. Army Engineer Waterways Experiment Station (WES), under the sponsorship of the U.S. Army Environmental Center (AEC), was tasked to demonstrate and evaluate the hole sealing (grouting) capabilities of the AEC/WES Tri-Service Site Characterization and Analysis Penetrometer System (SCAPS). The AEC Project Officer was Mr. George Robitaille.

The project involved the joint WES efforts of the Geotechnical, Structures, Information Technology, and Environmental Laboratories and the SCAPS Program Management Office. The U.S. Army Engineer District, Vicksburg, Geotechnical Section, provided drill rig sampling support under the guidance of Mr. Jimmy Gray.

This report was prepared by Mr. Landris T. Lee, Jr., Engineering Geophysics Branch (CEWES-GG-F), Geotechnical Laboratory (GL). The work was performed under the direct supervision of Mr. Joseph R. Curro, Jr., Chief, Engineering Geophysics Branch (CEWES-GG-F) and under the general supervision of Drs. A. G. Franklin, Chief, Earthquake Engineering and Geosciences Division, and W. F. Marcuson III, Director, GL. Technical guidance and assistance was provided by Drs. W. N. Brabston and P. G. Malone, Engineering Sciences Branch, Concrete Materials Division, Structures Laboratory.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02832	cubic meters
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]
feet	0.3048000	meters
gallons	3.785412	liters
gallons/minute	0.06309	liters/second
ounces	0.27801	newtons
inches	25.4	millimeters
inches/second	2.54	centimeters/second
inches/hour	0.0254	meters/hour
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic yard	1.6875	kilograms per cubic meter

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9)(F - 32). To obtain Kelvin (K) readings, use K = (5/9)(F - 32) + 273.15.

1 Introduction

Background

In the United States there are numerous locations where site investigations are being conducted to assess the geological, hydrogeological, and possible subsurface contamination conditions. During the course of those site investigations, numerous boreholes and penetrometer holes are being placed in the ground subsurface. Many of these drilled or pushed holes penetrate the groundwater saturated zone and provide potential conduits for the transfer of contaminants into the local groundwater (Figure 1). The open boreholes or penetrometer holes must be properly sealed prior to the completion of the site investigation to prevent any potential cross-layer contaminant transfer through the subsurface.

Exploratory boreholes are usually left open during the course of the site investigation to allow for collection of hydrogeological and subsurface contaminant data. Should the boreholes be used as permanent monitoring wells, the purpose of hole sealing is to enable accuracy of sampling, i.e. to provide proper sealing above and below the well screen. Should the borehole not be used as a permanent monitoring well, it is required to be properly sealed in accordance with applicable regulations. Typically, the sealing material (commonly called "grout") is pumped into the borehole to form a plug that seals the boring from the bottom to the surface. As a general rule, most states with borehole sealing regulations require the sealing material to be a neat cement slurry consisting of 5 to 7 gal of water per each 94-lb bag of Portland cement (slightly less than a 1:1 water to cement ratio by volume). The requirements for admixtures such as bentonite also varies between states, as do requirements for sealing through groundwater aquifers (National Research Council 1995).

As compared to drilled boreholes, direct-push technologies such as the cone penetrometer are becoming more commonplace in the site investigation arena. A cone penetrometer system pushes a steel rod containing sensors and/or samplers into the subsurface soil and collects in situ data. Current penetrometer-based systems typically seal the penetration with grout injected through an internal tube in the rod. Grout is ejected through the tube tip

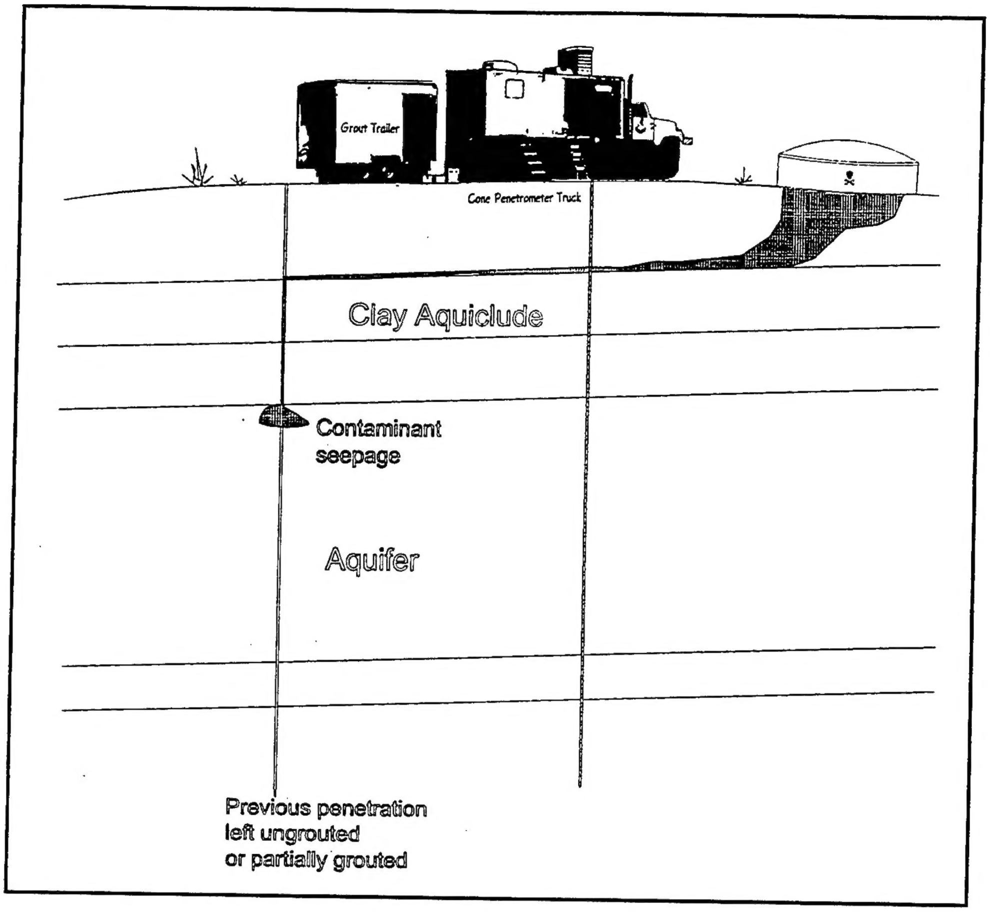

Figure 1. Potential contamination transfer resulting from unsealed subsurface penetrations

("expendable-tip" grouting) to seal the hole as the rod is withdrawn (Cooper et al. 1988; Robitaille 1994).

Typically, grout injection using a cone penetrometer accomplishes the singular purpose of filling the open hole left as the penetrometer rods are retracted. Other purposes for grouting may include soil compressibility reduction, soil density increase, and groundwater seepage control. These functions are achieved using grouting practices such as fracture grouting, compaction grouting, jet grouting, compensation grouting, massive fill grouting, and permeation grouting. The use of compaction grouting to increase soil strength and reduce seismic liquefaction potential are relatively recent developments (Warner, et al. 1992). Compaction grouting is a likely candidate for use with the cone penetrometer although it is not currently practiced. Although new applications for penetrometer grouting are being explored and developed, fill-grouting through the expendable tip during rod retraction was the only technique evaluated for this report.

Penetrometer fill-grouting may be accomplished by means other than the expendable tip method. The simplest procedure is to pour grout into the open hole left after the penetrometer rod has been fully retracted. This method

works only when the hole remains open and the groundwater aquifer has not been penetrated. A variation of this procedure is to insert a polyvinyl chloride (PVC) pipe down the open hole and pour or pump grout through the pipe. For grout delivery through the penetrometer rods, typically the open hole is re-entered with an open rod string, and the grout is poured or pumped down through the open rods. The rod string end is protected by a cap or other device to prevent soil entry prior to grouting. The rod string is retracted as the cap is disengaged and grout flow commences. Another variation is retraction grouting through the penetrometer rods via grout ports in an adapter ring. Grout reaches the ports either through the internal rod opening or through a designated grout tube. Example cone penetrometer grouting methods are illustrated in Figure 2.

Retraction grouting is not typically used for cone penetrometer soil sampling operations, due primarily to grouting equipment unavailability. Most of the current soil and groundwater sampling tools attached to the penetrometer rods do not allow retraction grouting through an expendable tip. Open hole or re-entry grouting practices are commonly used instead. One sampling tool that does allow for retraction grouting during sampling operations is the Multiport Sampler (Leavell and Lee 1995).

Objectives

The objective of this project was to demonstrate and evaluate fill-grouting (hole sealing) capabilities using a cone penetrometer in the retraction grouting mode. This project utilized laboratory experience gained from a previous project for grout material selection (Bean, et al. 1995) and applied those results and recommendations to a field setting. The cone penetrometer was used to inject grout seals into the subsurface at different site locations. The grout material behavior was observed during placement and after in situ curing.

The specific objectives were:

a. Evaluate behavior of selected grout materials and placement techniques during small diameter (< 2 in) grouting operations using a cone penetrometer.

b. Evaluate in situ interaction between grout and surrounding soil materials during grout placement and after curing.

c. Recommend guidelines for grout material selection and placement techniques for cone penetrometer retraction grouting operations.

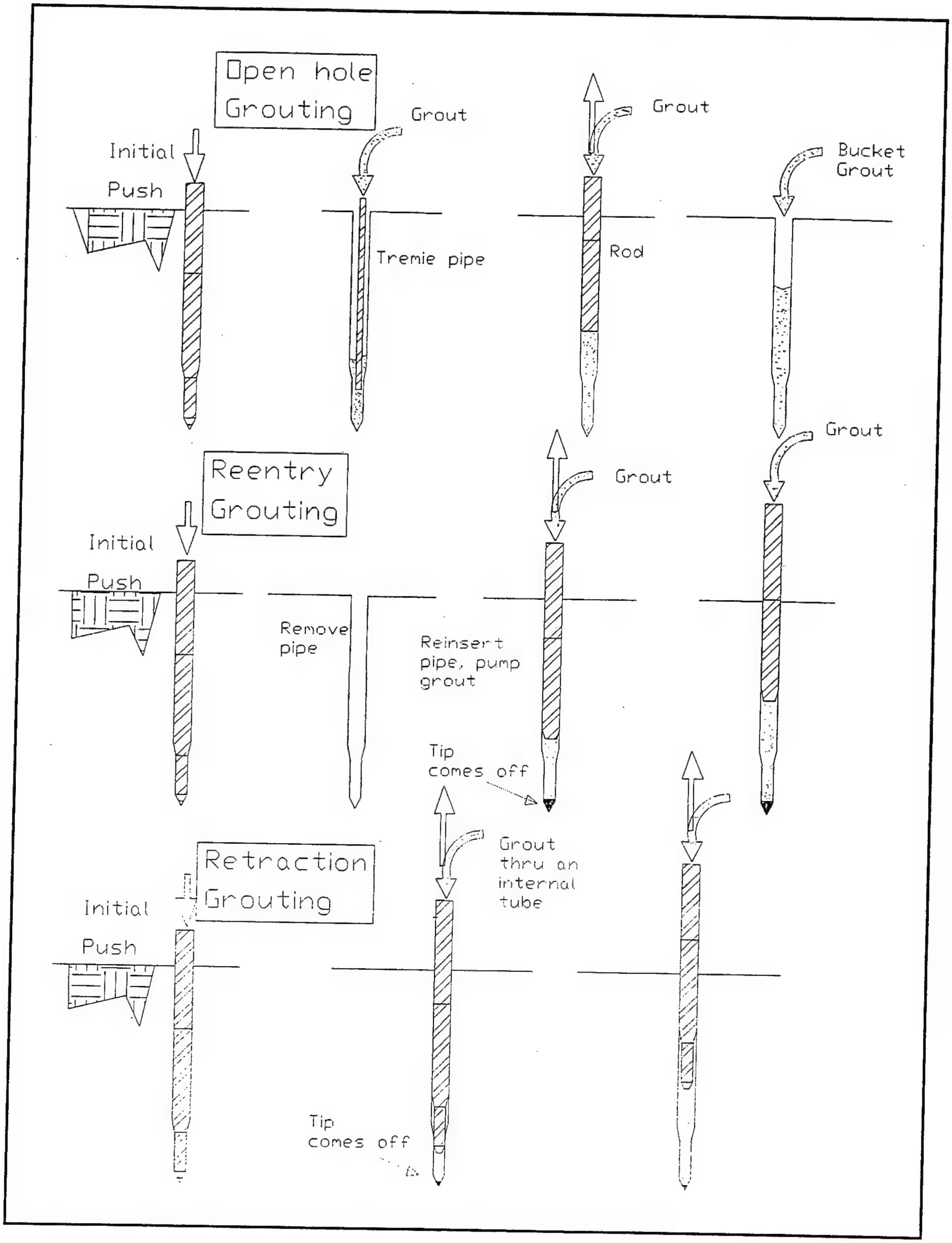

Figure 2. Some of the cone penetrometer borehole grouting methods

Approach

Several factors were considered for achieving the above goals. Previous penetrometer grouting project experiences, published results from other grout research efforts, and current penetrometer grouting equipment usage and techniques were reviewed for the purpose of targeting the most viable strategy to achieve useful results.

Particulate (mineral) grout materials were used in this project since they are essentially the grouting industry norm for borehole sealing materials (National Research Council 1995). Chemical grouts are not typically used because of groundwater toxicity concerns and operator handling safety requirements, although some types of chemical grouts such as one-part polyurethane grouts are readily adaptable for use with a cone penetrometer. For the purposes of soil permeability reduction and water seepage reduction, polyurethane grouts are excellent candidates for usage in situations where toxicity concerns are not paramount (Naudts 1995). The silicate-based grouts are the most common chemical grouts used for soil strengthening and seepage control, especially in Japan (Shimada, et al 1992). One advantage of silicate-based grouts is their lower toxicity, but shrinkage problems are common (Jefferis and Bahai 1995).

Sites with geology amenable to cone penetrometer operations were selected for field grouting evaluation. Typical cone penetrometer operations are generally limited to sites with unconsolidated subsurface strata such as sands, silts, and clays. The field evaluations were conducted at sites containing distinct subsurface layers of predominately sandy, silty, or clayey soil materials. Grouting was conducted both above and below the groundwater table to evaluate the effects of grouting in different groundwater environments. The following matrix was proposed for the grouting evaluation project:

Table 1
Evaluation Matrix

Soil Type	Grout Material	Pumping System	Saturated Soil	Unsaturated Soil
Sands	X	X	X	X
Silts	X	X	X	X
Clays	X	X	X	X

2 Equipment and Materials

Grouting Equipment

The grouting platform consisted of the AEC/WES Site Characterization and Analysis Penetrometer System (SCAPS) grouting system. Specifically, the grout was mixed, pumped, and delivered using the SCAPS cone penetrometer retraction grouting system. For information about the SCAPS, see the listed references (Department of the Army, 1996; Cooper, et al, 1993). The SCAPS grouting program has encompassed an evolving process of different equipment, materials, and procedures for a wide array of sites and weather conditions expected to be encountered during a typical cone penetrometer site investigation or demonstration.

The initial SCAPS grouting equipment was designed for two-component chemical grouting, and consisted of tandem airless pressure piston pumps each connected to a 1/4 in. diameter plastic tube (Figure 3). The tubes were routed through the penetrometer push rods and terminated at an expendable tip in the bottom rod. Each of the pumps fed a liquid chemical grout, and the two chemicals were mixed as the 1/4 in. tubes merged near the expendable tip. The grout chemicals consisted of hydrophillic urethanes, sodium silicate and calcium chloride, polyacrymide, or other chemical experimental mixtures. As grouting was performed at more environmentally sensitive sites during the SCAPS early developmental period (between 1986 and 1992), the regulatory climate was leaning away from usage of such chemical grouts. Particulate grouts (Portland cement, bentonite, attapulgite, gypsum, etc.) were selected as the most likely candidates to replace chemical grouts. Experiments with mixtures of chemical and particulate grouts were conducted. As the usage of particulate grouts increased, their pumpability using the airless pumps with the 1/4 in. diameter tubing significantly decreased. Experimentation using a single airless pump with a larger diameter grout tube was conducted, and particulate grouting during one field investigation was performed for a short duration until the equipment began to fail because of excessive pumping stress. The next goal was to obtain equipment better suited for particulate grout pumping.

The airless pump setup was replaced soon afterwards by a Moyno™ progressive cavity rotor driven by hydraulic fluid pressure. The hydraulic fluid

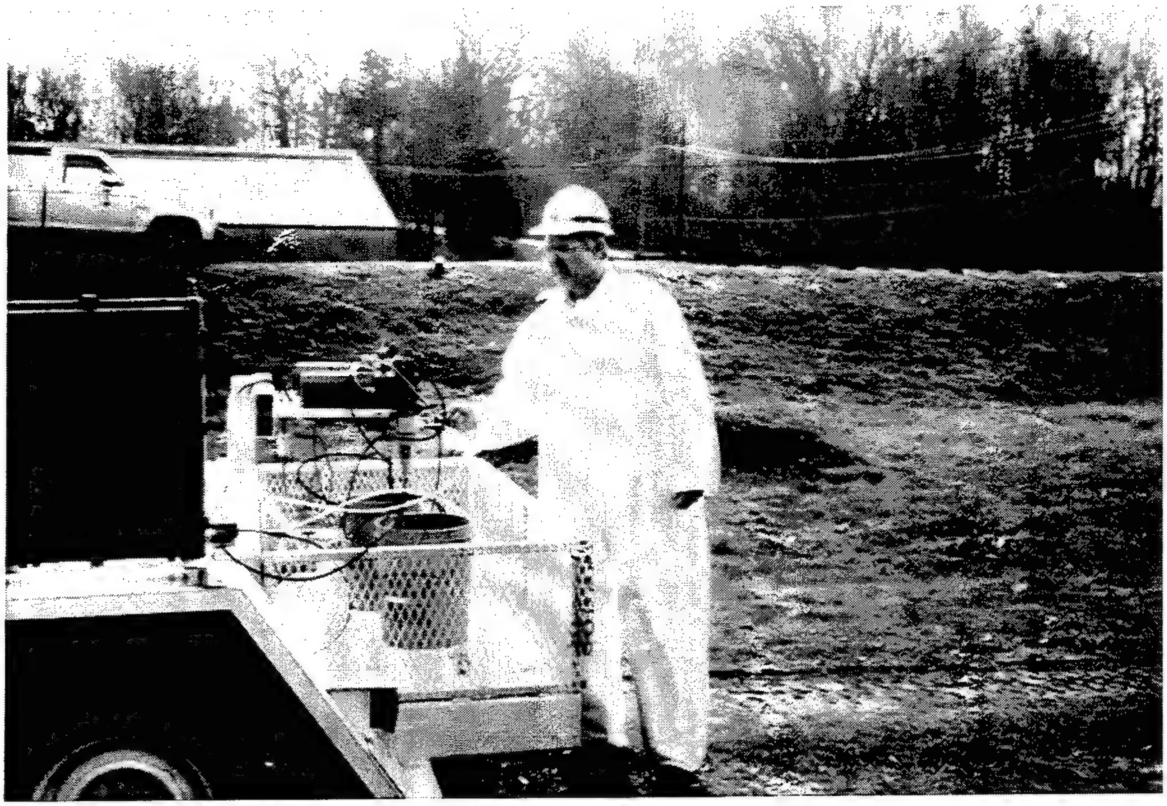

Figure 3. Original SCAPS grouting system utilizing twin airless piston pumps and 1/4-in.-diameter grouting tubes

was delivered from a hydraulic pump powered by an electric motor (Figure 4). The grouting tube diameter was increased to 3/8 in., and this setup performed much better than the previous grouting system. Several site investigations were successfully conducted using the retraction grouting method to seal the penetrometer holes. Equipment problems typically centered around the hydraulic pump; during hot weather it tended to overheat, and during cold weather it was sluggish. Pumping rate was manually controlled by the grout operator, and care had to be taken to ensure that the grout was being pumped in close coordination with the push rod retraction cycle. Otherwise, excess grout tended to penetrate the laser-induced fluorometer sensor optical window socket, requiring frequent downtime for cleaning maintenance.

The current grouting setup eliminates the hydraulic pump and motor. An electric motor drives the progressive cavity rotor and the motor is controlled by a motor controller panel (Figure 5). The motor may also be controlled at a remote station such as the push operations room. The recirculation valve remains manually activated.

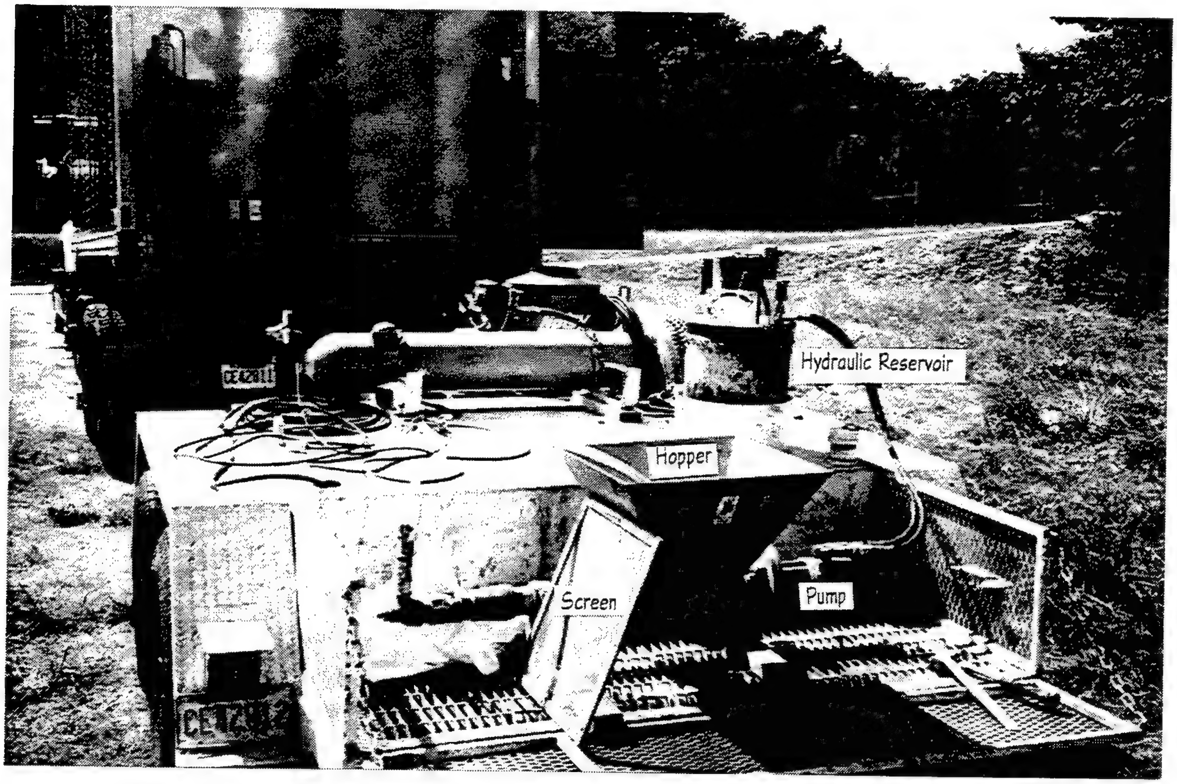

Figure 4. Second-generation SCAPS grouting system, consisting of a single progressive cavity pump and a 3/8-in.-diameter grouting tube

Grouting Materials and Procedures

Materials

The current grouting material consists of Type I portland cement and potable fresh water. Other particulate materials have been evaluated for use with the cone penetrometer, including calcium hydroxide-actived, slag-based grouts (Bean, et al. 1995). The off-the-shelf availability and widespread acceptance of portland cement-based grout highlights its merits for continued usage in field borehole sealing. For consistency, only one brand of portland cement was used (Lonestar^{TM}); earlier experiments indicated slight inconsistencies in mix properties when varying brands. Selected admixtures to increase pumpability, reduce grout shrinkage, and increase time for setting were also used.

Grouting procedures

As the cone penetrometer rod was advanced through the subsurface collecting in situ data, preparations to mix grout were initiated so the grout material would be ready for pumping as soon as the penetrometer rods began to be retracted.

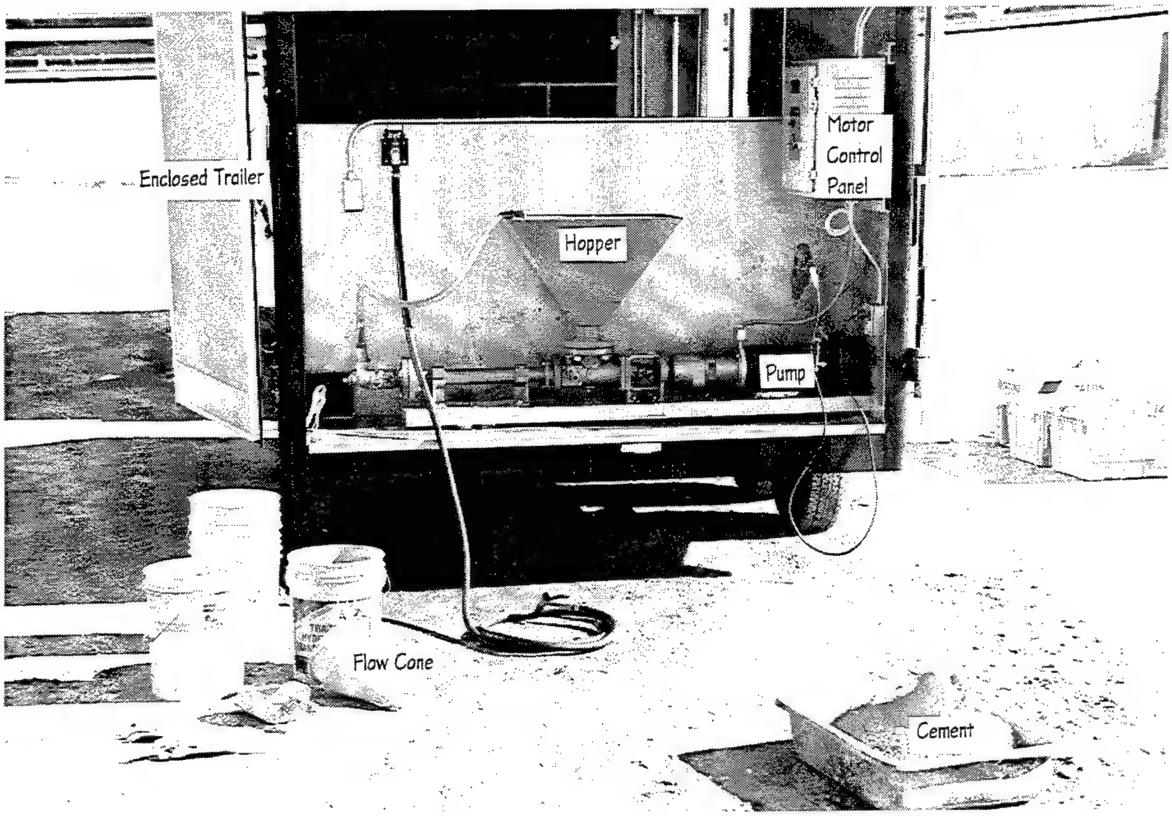

Figure 5. Current SCAPS grouting system

The grout mixture was proportioned using 5-gal buckets and a spring weight scale. The desired amounts of portland cement, water, and admixtures (if used) were measured by weight or volume in a 5-gal bucket and agitated with a small 120 volt hand drill (double insulated and on a ground fault interrupter circuit for personnel safety). The usefulness of mixing more than a 5-gal batch at one time was limited because of the grout pump hopper size (approximately 5 gals) and the typical small penetration hole volume to be sealed.

During hot or cold weather operations, precautions to prevent deleterious effects began at the grout mixing stage. When the ambient temperature was greater than 90 deg F, the grout had be pumped within less than 30 min or sucrose (table sugar) in the amount of one packet per 5 gal bucket (maximum dosage of 0.15 percent by weight per weight of cement) was added to reduce the chance of rapid hydration. When the ambient temperature was in the upper 20's (deg F), ice formed at various pump connections and fittings, restricting the grout flow. The grout began to freeze if left exposed in the hopper without constant agitation.

Prior to commencement of each pumping operation, the grout was manually poured through the hopper screen to remove lumps (Figure 6). The electric grout pump was then switched on, and the grout was recirculated within the hopper by manually opening the recirculation valve (Figure 7). Samples

Figure 6. Pouring grout mix through the hopper screen

of grout viscosity were taken using the ASTM C 939 flow cone method (ASTM 1988b) for record-keeping purposes. At the desired time, the grout in the hopper was pumped through the grout tube down through the penetrometer rod segments.

The grout was pumped within an internal 3/8 in. diameter tube through the penetrometer rods as they were withdrawn through the subsurface. The expendable penetrometer rod tip was ejected by grout pressure, and the grout flowed into the open penetration hole. As the rods were retrieved in 3 ft (1 m) intervals, the recirculation valve was closed and then opened once the retrieval was complete. The pump rate was preset at the motor control panel. The rod operator signaled the beginning and end of the rod retraction cycle, and the grout operator manually switched the recirculation valve accordingly. The grout delivery rate was a function of the soil type, the grout mixture, the pump speed, and the speed of the rod operator during rod retraction. The desired achievement was to observe the grout at the top of the ground surface as the last rod emerged above the ground surface.

After the hole was grouted, the grout tube was emptied of grout and flushed with clean water to prevent blockages from hardened grout. The grout pump and hopper were cleaned also. At the end of each day's operations, the grout pump connections and tube fittings were removed and cleaned.

Figure 7. Recirculating grout into the hopper

Grout retrieval procedure

After a period of in situ curing (typically one month) grout column sections were retrieved from the subsurface and evaluated. An oversized core barrel sampler was advanced around the periphery of the grout column using a geotechnical drill rig. The core barrel centered the grout column, severed the grout column's vertical continuity, and pulled the grout column with surrounding soil intact out of the ground. At the surface, the core barrel was placed in a hydraulic extruder, and the grout column section with surrounding soil was extruded from the core barrel. The process was repeated to as deep as possible, and the grout column was retrieved one section at a time. Vertical alignment of the grout column, vertical alignment of the drill rig, and soil conditions determined the maximum retrieval depths. Figures 8 and 9 show the grout retrieval process.

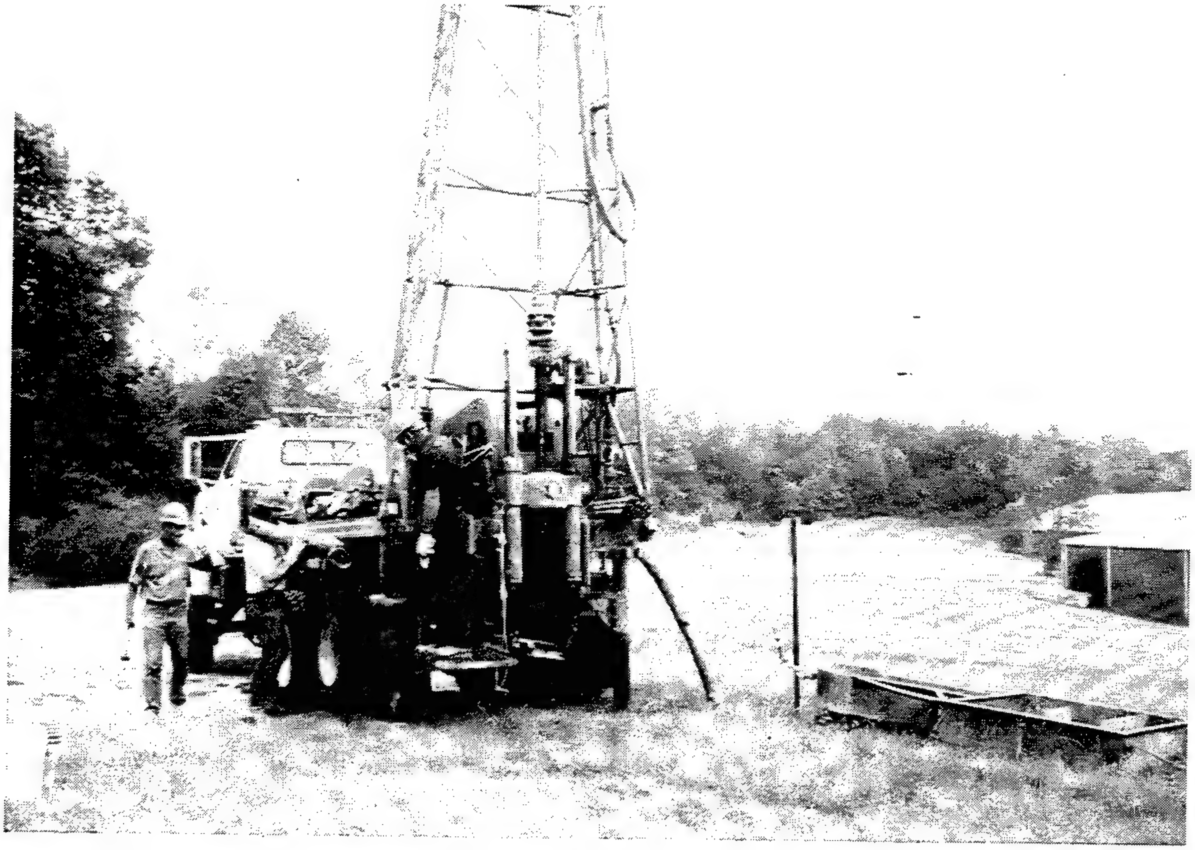

Figure 8. Drill rig preparations for retrieving grout columns

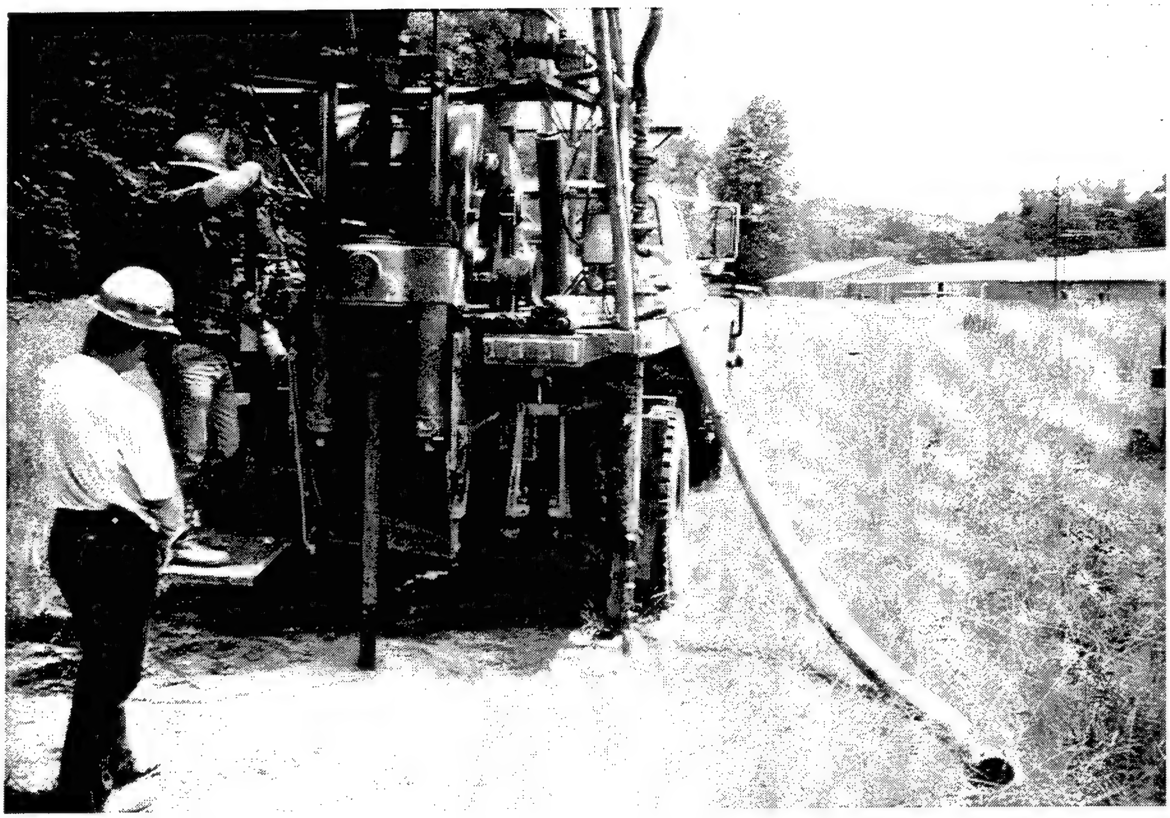

Figure 9.   Small diameter core barrel inserted over a grout column

3 Results and Evaluation

Site 1

The soil material at Site 1 (located at the WES) was predominately clay and was penetrated to a depth of approximately 60 ft in two locations with 1.75 in.-diameter rods. The sampled soil observed in the upper 19 ft was dark gray lean clay (CL) according to the Unified Soil Classification System (USCS). Water saturation depth was approximately 10 ft. The hydraulic conductivity of the soil ranged from approximately 1×10^{-6} cm/sec to 1×10^{-7} cm/sec, and was obtained from ASTM D 2435 soil consolidation tests (Appendix A).

Grout sealing was accomplished during the rod retraction cycle. Each hole was grouted with a different mixture; the first mixture was a gypsum cement and portland cement batch, and the second mixture was a portland cement batch with a water/cement ratio of 1:1 by volume (2:3 by weight). The gypsum cement mixture was difficult to pump because of early onset of hydration caused by the summer 95 deg F. ambient temperature, and extra water was added to prevent a "flash" set. The second mixture (portland cement) had a higher pumpability and did not hydrate prematurely because of the addition of sucrose as a set retarder. Grout take in each hole was slightly more than the open hole volumes (approximately 10 percent greater).

Eight months later, the site was revisited for the purpose of evaluating the in situ grout columns. A set of surface water infiltration tests were conducted to observe the influence of vertical infiltration due to the presence of grout columns in the soil. A single-ring infiltrometer test using an open-bottomed 2 ft diameter metal container was performed over each grout column and once on the adjacent natural ground surface. The container was filled to a designated point with water and the water infiltration into the ground surface was noted. The results indicated the vertical infiltration into either of the grouted soil surfaces was not greater than the vertical infiltration into the adjacent natural ground surface. The average infiltration rates into the grouted surfaces were 0.4 in./hr (gypsum column) and 0.6 in./hr (portland cement column); the average infiltration rate into the adjacent natural ground (ungrouted) surface was 0.7 in./hr. These results indicate that the grout columns were not preferential pathways for vertical infiltration from the ground surface.

The grout columns were extracted from the subsurface using a small-diameter "undisturbed" sampler core barrel pushed with a drill rig. The rig was positioned over each grout column in order to center the core barrel over the column. The barrel was slowly advanced downward over the grout column, and was pulled back out after the barrel reached full travel (approximately 4 ft). The intact grout column sections with surrounding soil were then hydraulically extruded and the column sections were visually analyzed for grout continuity and condition.

The maximum depth of grout column retrieval was 19 ft below ground surface (bgs). Further depth retrieval was not possible due either to misalignment of the penetrometer bore hole during penetration or misalignment of the drill rig mast during grout column extraction. Several attempts were made to reposition the core barrel exactly over the grout columns, and most attempts did not yield satisfactory results. Changing to a larger (5 in. diameter) core barrel yielded better results.

The grout columns were separated from the surrounding soil material and their physical condition was observed. Figure 10 shows representative grout samples obtained from this site. The following observations were noted:

a. The grout column center had settled approximately 1 ft bgs although the column outer shell extended to the ground surface. Outer shell thickness was approximately 1/2 in. to the 1 ft bgs depth. At that depth and for the remainder of the retrieved sample depth, the grout column was solid, with a 1-5/8 in. diameter.

b. No gaps in the grout column sections were observed, and the grout was fully cured. The grout appeared to tightly fill the penetrometer hole, and at one point where the grout was "necked down" (i.e. smaller diameter), the surrounding soil tightly wrapped the grout column. The reduced diameter grout was most likely caused by reduced grout flow during the beginning or end of a rod retraction cycle.

c. No internal cracks or voids were observed in the grout. Such cracks or voids would increase the likelihood of vertical or horizontal permeation from groundwater or contamination sources.

d. The exterior surface of the grout column had a smooth texture, but there were locations where the surface was dimpled with small ridges (less than 1/32 in protrusions).

e. The presence of saturated soil conditions did not appear to affect the grout condition. The grout cured below the water table had the same appearance and texture as the grout cured above the water table.

Representative portland cement grout samples (4 in. length) were tested for water-saturated hydraulic conductivity in the laboratory. A hydraulic conductivity chamber apparatus used for concrete testing was loaded with the grout sample and the chamber was pressurized to force water through the grout.

Figure 10. Grout column sections with surrounding soil removed

No results were obtained because the samples could not be saturated with water, even after a chamber pressure increase to 1000 psi. Such a test indicated that the grout was virtually impermeable to naturally occurring groundwater gradients.

Site 2

The soil material at Site 2, located at the WES Engineering Geophysics Experiment Site, was predominately silt (USCS ML), and was penetrated at four locations with a 1.75 in.-diameter rod. Each penetration hole was approximately 15 ft deep into the soil vadose zone. Retraction grouting was performed through a 3/8 in. diameter, 150 ft length internal grout tube with an expendable tip at the downhole end.

One hole was grouted using a portland cement mix with a water to cement ratio of 0.58:1 by volume (1:2.5 by weight), 1.65 percent bentonite by cement weight, and 5.2 oz. of a water reducer additive (Sikament™). The ASTM C939 flow cone rate was 14 sec, and the downhole pumping rate was 0.34 gal per min. The purpose of the water reducer additive was to increase the pumpability after adding bentonite. Another hole was grouted with a water cement

ratio of 1.4:1 by volume (1:1 by weight) with aluminum sulphate grout expansion additive of 1 percent by weight. The aluminum sulphate additive was intended to cause grout expansion in the hole as the grout cured in order to provide an even tighter seal between the grout/soil interface. Flowcone rate was 8 seconds and the downhole pumping rate was 0.83 gal per min. The remaining two holes were grouted but the grout columns were not retrieved.

The grout was left to cure in situ for approximately one month prior to retrieval. The same procedure for retrieval as used at Site 1 was performed at this site. At the time of sample retrieval, the soil was extremely dry and hard which caused difficulties in accurately retrieving and extruding the grout columns. During the one-month curing period, the soil had not received any rainfall infiltration. The first grout column was retrieved from a depth of 8 ft after several attempts were made to center the core barrel over the grout column. The second grout column was retrieved from a depth of approximately 13 ft.

After retrieval, the grout columns were removed from the surrounding soil, and the grout and soil conditions were evaluated. The soil material was a light tan silt that was extremely hard, dry, and uniform for the full depth of penetration. Hydraulic conductivity for this soil ranged from 1×10^{-5} cm/sec to 1×10^{-6} cm/sec, based on soil consolidation results (Appendix A).

The following items were noted regarding the retrieved grout sections:

a. The first grout column exhibited no settlement during the curing period, and the column diameter was approximately 1-5/8 in. The second grout column appeared to have settled approximately 2 ft with an upper outer shell thickness of approximately 1/2 in. For the remainder of the column, the grout diameter was approximately 1-1/4 in. The second grout column contained an expansion agent (aluminum sulphate) which did not expand either in situ or within identical grout samples (split samples) cured in the laboratory. The addition of the expansion agent may have contributed to the increased grout settlement below the ground surface and the decreased grout column diameter.

b. No ungrouted gaps in the grout column sections were observed, and the grout was fully cured. The grout appeared to tightly fill the penetrometer holes. The compressed soil around the penetrometer hole circumference was clearly visible with vertical and closely spaced striations extending to a distance of approximately 1 in. outward from the hole. The hole diameter (and subsequent grout column) had shrunk from an initial 1.75 in. open diameter down to a 1.62 in. sealed diameter. Figure 11 shows a grout column section with the surrounding soil left intact.

c. No internal grout cracks were observed. Some internal air bubble voids were present at various locations in the grout column containing the water reducer additive. Although the water reducing additive increased the pumpability and allowed for a thicker mix to be pumped downhole,

the presence of visible internal air bubbles may adversely affect the grout durability and permeability. Also, the environmental concerns for using such a chemical additive may outweigh its increased pumpability benefits at some environmentally sensitive sites.

d. The exterior surface of the grout had a smooth texture, and there were no observed surface dimples as noted at the previous grout site.

e. The presence of unsaturated soil conditions did not appear to adversely affect the grout curing process or the condition of the cured grout.

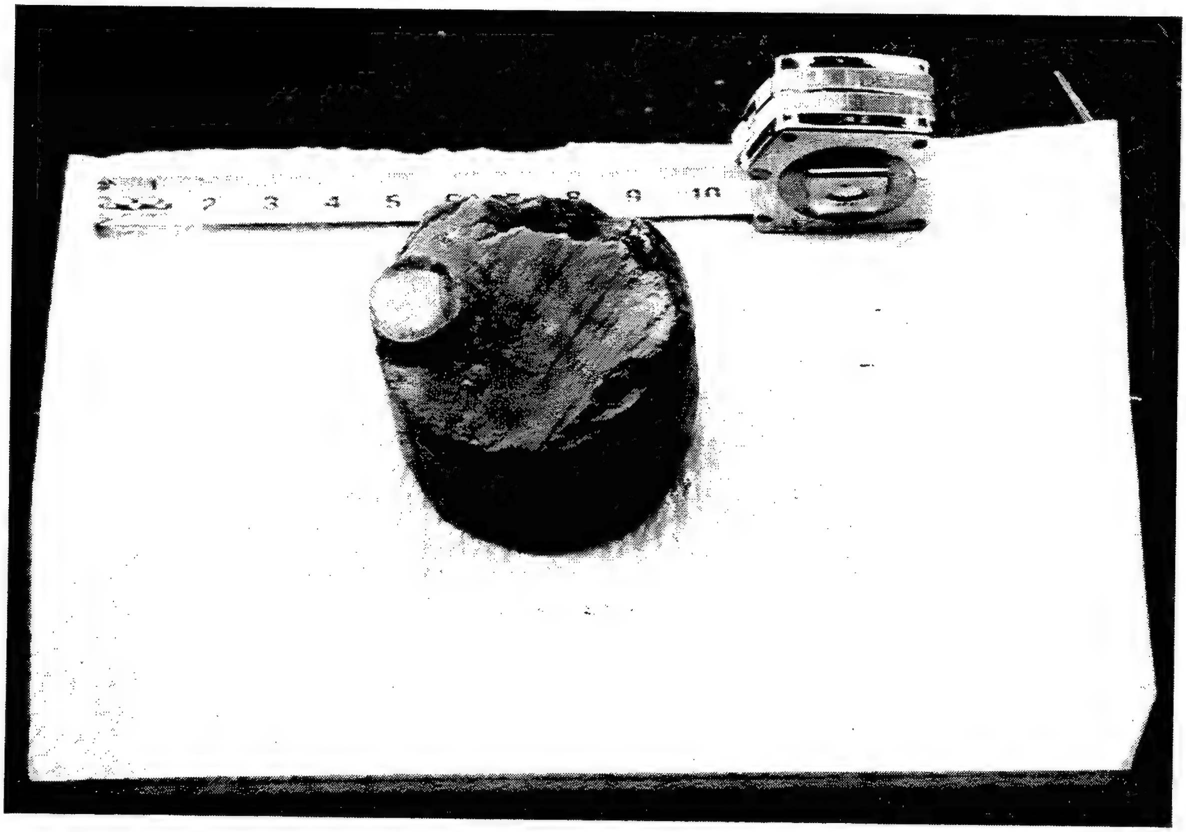

Figure 11. Grout column section with surrounding soil left intact

Site 3

Site 3, located near the Mississippi River at Natchez, Mississippi, was selected as an evaluation location because of its predominately sandy material. The soil stratigraphy was mapped with the SCAPS cone penetrometer at five locations, and retraction grouting using a 1.75 in. diameter rod with the 3/8-in. diameter grouting tube arrangement was conducted. Each penetration was approximately 17 ft depth bgs. The water table was located 13.5 ft bgs at the time of grouting. Hole 1 was left open for conducting water table depth measurements. The remaining four holes were grout-sealed during rod

retraction. The grout mix used in each hole was progressively thicker (i.e. more viscous).

A water to cement ratio of 3:1 by volume (2:1 by weight) portland cement grout mix was pumped into the first grouted hole (hole 2). The mix was very fluid (ASTM C 939 flowcone rate of 8.1 sec) and was easily pumped. The pump rate was approximately 1.5 gal per min. The grout take was approximately 4 gal which was twice the hole volume. The increased grout take was likely due to grout infiltration into the coarse grained soil strata.

The mixture in hole 3 had a water to cement ratio of 2.25:1 by volume (3:2 by weight) and a flowcone rate of 9 sec. Pump rate was approximately 1.5 gal per min, and the grout take was twice the hole volume.

The mixture in hole 4 had a water to cement ratio of 1.5:1 by volume (1:1 by weight), and a flowcone rate of 9 sec. Pump rate was approximately 1.5 gal per min, and the grout take was approximately 175 percent of the hole volume.

The mixture in hole 5 had a water to cement ratio of 0.75:1 by volume (0.5:1 by weight), and a flowcone rate of 9 sec. Pump rate was approximately 1.2 gal per min, and the grout take was slightly less than the previous hole (150 percent). This mixture pushed the limit for pumpability; the grout in the hopper began to form lumps. During warmer weather, the addition of sucrose or other approved retarder would have been required to prevent premature set.

The grout settled below ground surface in all the holes within a two hour period after grouting. An additional volume of less than one gallon per hole was needed to "top off" the grout columns to compensate for the grout settlement. During the grouting of each hole, extra effort was made to have the grout at the ground surface as the last penetrometer rod was retracted. For this sandy site and at a pump rate of approximately 1.5 gal per min, it was determined that an additional 15 sec of pumping time per rod retraction cycle was required to achieve such efficiency.

The grout was left to cure in situ for 46 days. The site was then revisited for the purpose of retrieving the cured grout and evaluating its condition. The first hole (left ungrouted) was checked, and the water table depth was 10 ft, which was 3.5 ft higher than the original depth of the water table at the time of grouting.

A drill rig was positioned over hole 2, and a 6 ft-long mud-lubricated rotary core barrel was advanced through the sandy soil subsurface. The core barrel differed from that used at previous sites in that it was mud (bentonite and water) lubricated and consisted of a 4 in. diameter barrel sampler inside an outer 5 in. diameter barrel with cutting teeth. This sampler was used in lieu of the hydraulically - pushed core barrel because it is commonly used for sampling sandy soil strata.

The grout column at the ground surface had settled 2 in. The upper 2 ft of the grout column was excavated by hand and removed in order to accommodate the 6 ft rotary core barrel length within the drill mast setup. The core barrel was advanced at a slow rate (approximately 1 in. per second), with most of the lubricating fluid diverted into a mud pan instead of through the core barrel annulus. At a depth of 4 ft, the barrel advance was stopped and the sample was retrieved. Only small amounts of grout and soil were retained inside the barrel. The process was repeated to a depth of 9 ft, and except for a few broken pieces of hardened grout, no samples were retrieved.

At hole 3, a Standard Penetration Test dry tube sampler (2.5 in. inside diameter) was used to retrieve a grout column sample after the grout column was excavated to a depth of 18 in. The tube was advanced several feet, and after retraction, it was observed that approximately 6 in. of grout column had been retrieved. The grout was highly fractured, probably caused by the percussive advancement of the sampling tube. The rotary core barrel was then set up and drilled to approximately 7 ft. No appreciable amount of sample other than a few broken chunks of hardened grout and a 6 in. length of sandy soil were retained in the sampler.

At hole 4, the rotary core barrel was again tried, but with limited success because most of the sample was lost during retraction.

At hole 5 (the thickest grout mixture) the grout column was excavated to a depth of 1 ft bgs to expose the grout column and achieve vertical alignment with the rotary core barrel. Three coring attempts to a total depth of 16 ft were made, but the amount of sample retained in the barrel upon retraction was minimal.

The following observations were made at this site:

a. A continuous column of cured grout was observed to a 2 ft depth. Below that depth, no continuous grout column sections were retrieved. The grout was retrieved as broken pieces which appeared to have cured very well but were probably broken during the sampling process.

b. The appearance and outer texture of the near-surface grout columns were similar to those of the grout columns at Sites 1 and 2. The grout was fully cured as an integral vertical column, with no apparent cracks or internal voids.

c. Grout placement at this site differed from Sites 1 and 2, due in part to the wider range of water to cement ratios, and the sandy subsurface soil. The mixtures with a higher water to cement ratio likely permeated the subsurface soil more readily than did the thicker mixtures. Compared to Sites 1 and 2, the amount of time for pumping each hole full of grout seemed to take longer at this site, although no direct comparisons of grouting durations were made because of the wide range of time delays involved in push rod retraction. In general, less grout was

needed to fill the hole when using thicker mixtures (lower water to cement ratio mixes).

d. Another variable affecting grout placement duration was the pumping rate. The best available method for determining pump flowrate was by measuring the grout outflow using a bucket and stopwatch. At Site 3, the pump was instrumented with a motor controller with an indicator for pump motor revolutions per minute (rpm) calibrated to water flowrate. The rpm gage was not calibrated to a grout flowrate as a function of grout viscosity. A better method to judge the grout "take" or flow into the hole would be to install and utilize a pressure gage in the grout tube. Variations in grout pressure would indicate whether or not the hole was full of grout and if grout was permeating the soil surrounding the hole.

e. Using a drill rig to retrieve grout samples from a partially saturated to saturated sandy soil had not been previously achieved. Obtaining soil samples in such an environment is notoriously difficult, and samplers used for obtaining soil samples were not readily adaptable to obtaining grout column samples. In most instances the grout column likely slid out of the sampler barrel before the barrel was brought to the surface. Such an observation was based on the small quantities of retrieved soil and grout. Sampling equipment designed for retrieving grout column samples was needed at this site. Unfortunately, such specialized equipment was not known to exist at the time of this project.

f. For deep penetrations requiring large grout volumes, the 5-gal buckets should be replaced with a grout colloidal mixer. Larger grout batches with better mixing quality control could then be achieved.

4 Discussion and Conclusions

Retraction grouting was performed at three different sites, and sections of the in situ cured grout columns with surrounding soil were extracted from the ground. The behavior of the grout material during placement, grout placement techniques, and the condition of the cured grout and its interaction with the sur-rounding soil were observed and evaluated. Although limiting the research scope to three sites constrained the possibilities for trend analysis from a larger database, useful data were obtained and evaluated. From this data, the following conclusions were drawn:

a. Penetration hole sealing by retraction grouting was highly effective. The likelihood of achieving a grout seal in an open penetration hole was maximized with retraction grouting. Although not evaluated in this report, tremie grouting and open hole grouting do not compare favorably to retraction grouting, based solely on previous field experience.

b. Portland cement grout was the preferred material. It was pumped in many different mixture configurations, and the material cured to a hardened state with higher strength and lower hydraulic conductivity than the surrounding soil. Portland cement grouts typically have hydraulic conductivities ranging from 10^{-6} to 10^{-10} cm/sec, and the addition of bentonite enables even lower hydraulic conductivity to be achieved (Lutenegger and DeGroot 1994). The grout material typically had a lower hydraulic conductivity compared to penetrated clays and silts which allow contaminant transfer. The hydraulic conductivity tests for the grout samples taken from the clay site demonstrated this conclusion to be valid. Studies have shown that, in the short term, a preferential pathway occurs along the grout/soil interface in laboratory specimens (Manila and Pierce 1994). Another study indicated that although a pathway occurs at the grout/soil interface, it is for a limited distance, and neat (portland) cements form rigid seals with low permeability and high durability (Edil, et al. 1992). The observed integrity of the grout and the soil at the grout/soil interface of the retrieved samples also supported this conclusion.

c. When grouting in sandy soil strata, a grout mixture with a lower water to cement ratio was required to minimize the amount of grout needed to fill the penetration hole. The effect of water to cement ratio variation

was not as prominent for the finer-grained soils as it was for the sandy soil. A flowmeter for volume measurement and a pressure gage indicating pressure build-up as the hole fills would enhance efforts to tailor the grouting operation and thus maximize effectiveness.

5 Recommendations

The following recommendations are made based on this evaluation project:

a. Establish a better control method for sequencing the rod retrieval operation with the grout pumping operation. Doing so would help ensure that grout is delivered down-hole as the rods are retracted, and thus eliminate "necking down" or discontinuities in the grout column due to premature shut-off of the grout flow as a rod is being retracted.

b. Utilize a pressure gage in the grout tube between the pump outlet and the expendable tip. A pressure gage monitored by the grout pump operator would ensure that the penetration hole is completely filled with grout. As the pressure builds to a predetermined point, the operator would know when to engage the recirculation valve and shut off the grout flow into the hole. Other useful items would be a grout flowrate meter calibrated for viscosity changes to monitor the grout placement efficiency and a colloidal mixer which would allow faster mixing of large batch volumes.

c. Use a water to cement ratio no leaner than 1.5:1 by volume and no thicker than 0.75:1 by volume for delivery through a 3/8 in.-diameter tube. The addition of admixtures to reduce shrinkage or increase flowability (pumpability) are generally not necessary or useful. During hot weather the addition of up to one sugar packet per 5 gal of grout mixture is acceptable to prevent premature set. Refer to Appendix B for estimated grout volumes and mixtures.

d. Further research in field performance, integrity, and durability of grout materials should be conducted as advancements are made in grout retrieval technologies. Specialized drilling equipment and techniques are needed to retrieve subsurface grout columns at diversified sites and from greater depths. In addition, methods and equipment for retraction grouting immediately after completion of soil and/or groundwater sampling events need to be developed to ensure that the penetration is completely filled with grout after the sampling event is completed.

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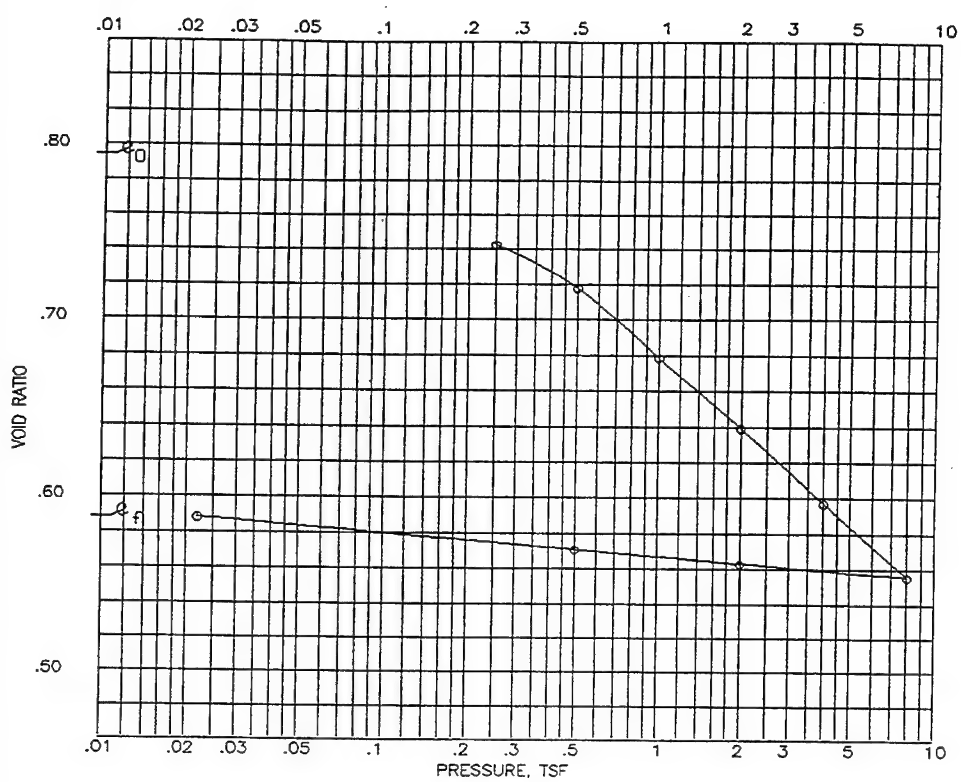
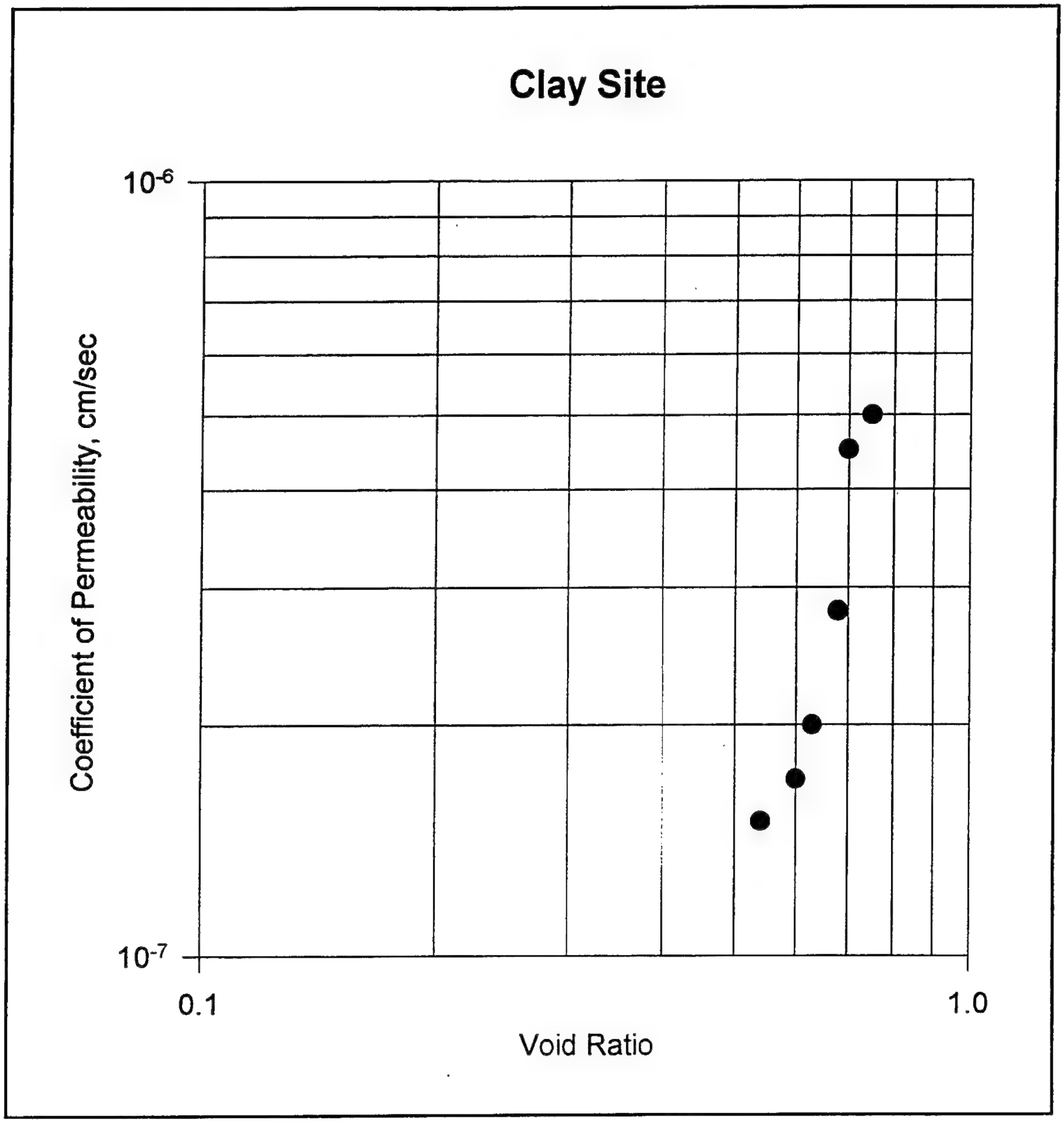
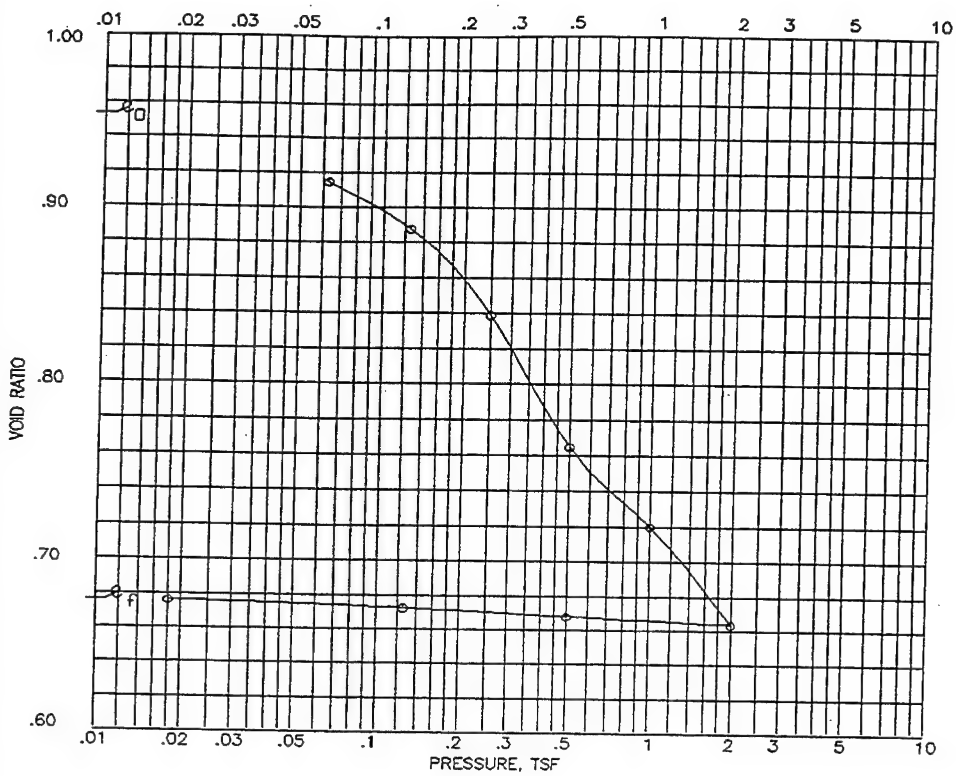
Appendix A
Soil Hydraulic Conductivity Tests



				BEFORE TEST	AFTER TEST
OVERBURDEN PRESSURE, TSF			WATER CONTENT, %	28.0	23.0
PRECONSOL. PRESSURE, TSF			DRY DENSITY, PCF	93.3	105.4
COMPRESSION INDEX			SATURATION, %	94.5	100 +
TYPE SPECIMEN	UNDISTURBED		VOID RATIO	.793	.588
DIA. IN 4.25	HT. IN 1.158		BACK PRESSURE, TSF		
CLASSIFICATION	SILTY CLAY (CL), GRAY				
LL	PL	PI	PROJECT SCAPS GROUTING		
GS 2.68 (EST)	D_{10}				
REMARKS:			BORING NO.	SAMPLE NO. 1	
			DEPTH/ELEV	TECH. JL	
			LABORATORY USAE WES – STF/GL	DATE 20 OCT 95	
			CONSOLIDATION TEST REPORT		

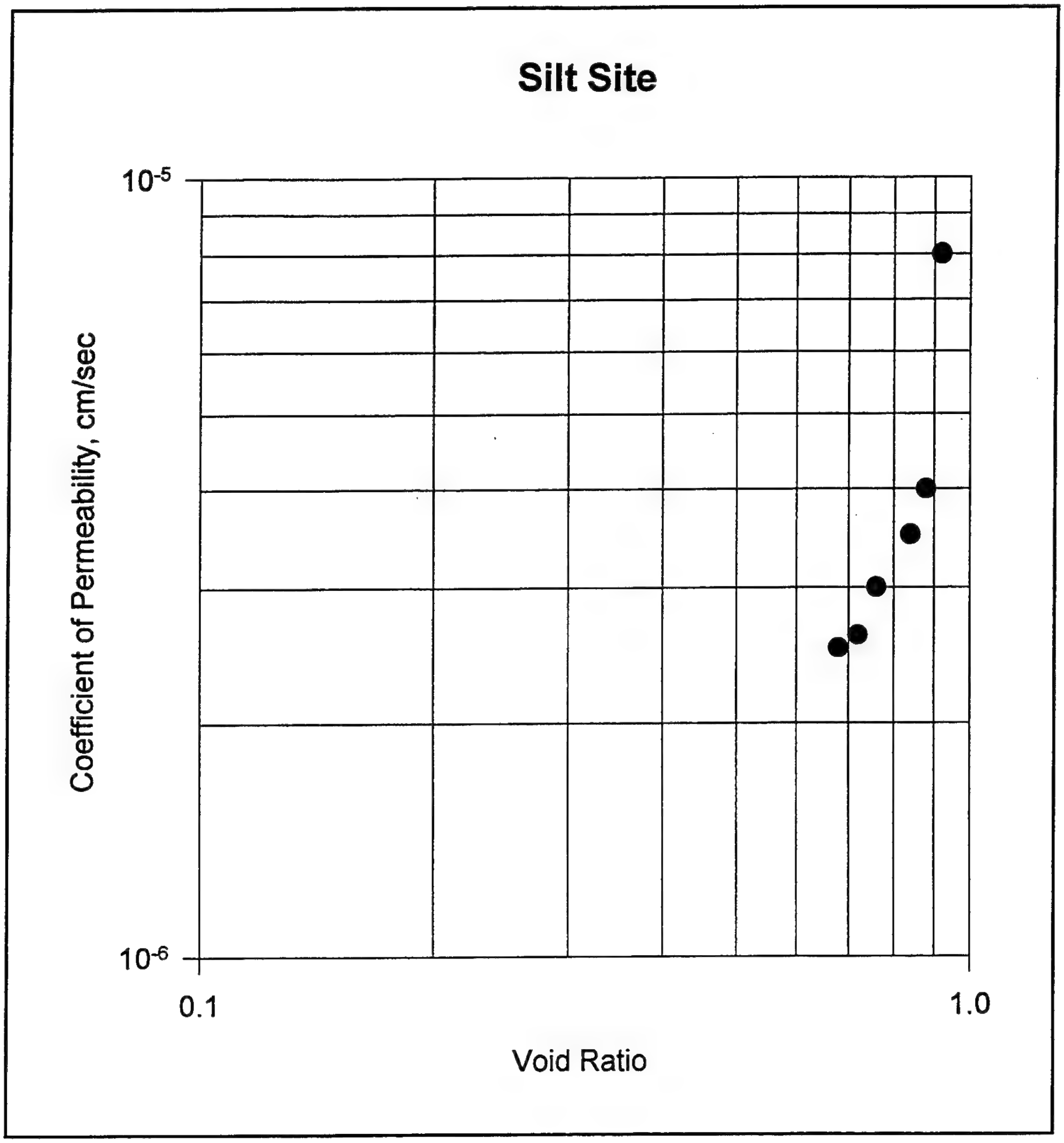
SHEET 1 OF 10


Clay Site
Coefficient of Permeability, cm/sec
10^{-6}
10^{-7}
0.1
1.0
Void Ratio



				BEFORE TEST	AFTER TEST
OVERBURDEN PRESSURE, TSF			WATER CONTENT, %	32.7	26.5
PRECONSOL. PRESSURE, TSF			DRY DENSITY, PCF	86.0	100.2
COMPRESSION INDEX			SATURATION, %	92.5	100 +
TYPE SPECIMEN	UNDISTURBED		VOID RATIO	.952	.676
DIA. IN 4.25	HT. IN 1.149		BACK PRESSURE, TSF		
CLASSIFICATION	SILT (ML), TAN				
LL	PL	PI	PROJECT GROUT EVALUATION		
GS 2.69 (EST)	D_{10}				
REMARKS:			BORING NO.	SAMPLE NO. 1	
			DEPTH/ELEV	TECH. JL	
			LABORATORY USAE WES – STF/GL	DATE 21 JUN 95	
			CONSOLIDATION TEST REPORT		

SHEET 1 OF 10


Silt Site
10^{-5}
10^{-6}
Coefficient of Permeability, cm/sec
0.1
1.0
Void Ratio

Appendix B
Grout Mixtures

The following tables provide assistance in estimating the total grout mix volume needed to fill a penetrometer hole using common water to cement ratios. These tables may apply to low-pressure retraction or open hole grouting. Tables are presented in both non-SI and SI units of measurement.

Procedure:

1. Estimate the depth of push and the expected soil type (sandy, more permeable deposits or clayey, less permeable deposits). Choose the table with the appropriate penetrometer rod size.

2. For a given push depth, the estimated grout volume needed for the soil type is shown. Choose the water to cement ratio (thick, average, or thin mixture), pick the estimated water volume and cement weight needed, mix, and pump.

Notes:

1. The given water to cement ratios are based on volume (ratio of a given water volume to a given cement volume), but the cement volume has been converted to weight. It is generally more accurate and convenient to measure the cement with a weight scale than to measure volumetrically.

2. The estimated grout volume for a clay soil is 1.1 times the hole volume, and for sand is 1.3 times the hole volume. These factors are estimates based on previous grouting experiments, and are highly variable. For example, a penetration in homogeneous clay or sand is rare, and the grout take depends on other factors such as saturation, density, and presence of unknown buried pipes. The tables are for guidance only and do not apply to all situations. Grout volumes are rounded off.

Formulas and conversion factors:

For a 0.75:1 ratio by volume, water (gal) = grout volume (gal) x 0.598
cement (lb) = water (gal) x 16.79
For a 1:1 ratio by volume, water (gal)= grout volume (gal) x 0.666
cement (lb) = water (gal) x 12.53

For a 1.5:1 ratio by volume, water (gal) = grout volume (gal) x 0.75
cement (lb) = water (gal) x 8.36

1 bag of 94-lb cement is 1 ft^3 bulk volume or 3.75 gallons solid (zero air voids) volume, and 25 lbs equals 1 gallon of zero air void volume.

1 ft^3 water = 7.5 gallons, and 1 gallon of water = 8.33 lbs. 1 gallon = 3.78 liters, and 1 lb = 0.45 kg.

To obtain water/cement ratio on a weight basis, multiply water/cement ratio (volume basis) x 0.67. For example, a 1:1 w/c by volume = 0.67:1 by weight.

Table B1
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in Low Permeability Soils (Clays). Rod Diameter = 1-3/8 in. (3.5 cm)

Depth, ft	Volume, gal		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, gal	Cement, lb	Water, gal	Cement, lb	Water, gal	Cement, lb
5	0.4	1	0.6	10.1	0.7	8.4	0.7	6.3
10	0.7	1	0.6	10.1	0.7	8.4	0.7	6.3
15	1.1	2	1.2	20.1	1.3	16.7	1.5	12.5
20	1.5	2	1.2	20.1	1.3	16.7	1.5	12.5
25	1.9	2	1.2	20.1	1.3	16.7	1.5	12.5
30	2.2	3	1.8	30.2	2.0	25.1	2.2	18.8
35	2.6	3	1.8	30.2	2.0	25.1	2.2	18.8
40	3.0	4	2.4	40.3	2.7	33.5	3.0	25.1
50	3.7	5	3.0	50.4	3.3	41.7	3.7	31.3
60	4.5	5	3.0	50.4	3.3	71.7	3.7	31.3
70	5.2	6	3.6	60.4	4.0	50.1	4.5	37.6
80	6.0	7	4.2	70.5	4.7	58.5	5.2	43.9
90	6.7	7	4.2	70.5	4.7	58.5	5.2	43.9
100	7.5	8	4.8	80.6	5.3	66.8	6.0	50.2
125	9.4	10	6.0	100.7	6.7	83.6	7.5	62.7
150	11.2	12	7.2	120.9	8.0	100.24	9.0	75.2

Table B2
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in High Permeability Soils (Sands). Rod Diameter = 1-3/8 in. (3.5 cm)

Depth, ft	Volume, gal		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, gal	Cement, lb	Water, gal	Cement, lb	Water, gal	Cement, lb
5	0.4	1	0.6	10.0	0.7	8.7	0.7	5.8
10	0.7	1	0.6	10.0	0.7	8.7	0.7	5.8
15	1.1	2	1.2	20.1	1.3	16.3	1.5	12.5
20	1.5	2	1.2	20.1	1.3	16.3	1.5	12.5
25	1.9	3	1.8	30.2	2.0	25.1	2.2	18.8
30	2.2	3	1.8	30.2	2.0	25.1	2.2	18.8
35	2.6	3	1.8	30.2	2.0	25.1	2.2	18.8
40	3.0	4	2.4	40.3	2.7	33.8	3.0	25.1
50	3.7	5	3.0	50.4	3.3	41.3	3.7	31.0
60	4.5	6	3.6	60.4	4.0	50.1	4.5	37.6
70	5.2	7	4.2	70.5	4.7	58.9	5.2	43.5
80	6.0	8	4.8	80.6	5.3	66.8	6.0	50.1
90	6.7	9	5.4	91.0	6.0	75.2	6.7	56.0
100	7.5	10	6.0	100.7	6.7	83.6	7.5	62.7
125	9.4	12	7.2	120.9	8.0	100.2	9.0	75.2
150	11.2	15	9.0	151.1	10.0	125.3	11.2	94.1

Table B3
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in Low Permeability Soils (Clays). Rod Diameter = 1-3/4 in. (4.4 cm)

	Volume, gal		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
Depth, ft	Open Hole	Estimated Grout Needed	Water, gal	Cement, lb	Water, gal	Cement, lb	Water, gal	Cement, lb
5	0.7	1	0.6	10.1	0.7	8.4	0.7	6.3
10	1.3	2	1.2	20.1	1.3	16.7	1.5	12.5
15	1.9	3	1.8	30.2	2.0	25.1	2.2	18.8
20	2.6	4	2.4	40.3	2.7	33.5	3.0	25.1
25	3.2	4	2.4	40.3	2.7	33.5	3.0	25.1
30	3.8	5	3.0	50.4	3.3	41.7	3.7	31.3
35	4.5	5	3.0	50.4	3.3	41.7	3.7	31.3
40	5.1	6	3.6	60.4	4.0	50.1	4.5	37.6
50	6.4	7	4.2	70.5	4.7	58.5	5.2	43.9
60	7.6	9	5.4	90.5	6.0	75.2	6.7	56.4
70	8.9	10	6.0	100.7	6.7	83.6	7.5	62.7
80	10.2	11	6.6	110.8	7.3	91.8	8.2	69.0
90	11.5	13	7.8	131.0	8.7	108.6	9.7	81.5
100	12.7	14	8.4	140.7	9.3	116.9	10.5	87.8
125	16.0	18	10.8	181.3	12.0	150.4	13.5	112.9
150	19.1	21	12.6	211.6	14.0	175.4	15.7	131.7

Table B4
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in High Permeability Soils (Sands). Rod Diameter = 1-3/4 in. (4.4 cm)

Depth, ft	Volume, gal		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, gal	Cement, lb	Water, gal	Cement, lb	Water, gal	Cement, lb
5	0.7	1	0.6	10.0	0.7	8.7	0.7	5.8
10	1.3	2	1.2	20.1	1.3	16.3	1.5	12.5
15	1.9	3	1.8	30.2	2.0	25.1	2.2	18.8
20	2.6	3	1.8	30.2	2.0	25.1	2.2	18.8
25	3.2	4	2.4	40.3	2.7	33.8	3.0	25.1
30	3.8	5	3.0	50.4	3.3	41.3	3.7	31.0
35	4.5	6	3.6	60.4	4.0	50.1	4.5	37.6
40	5.1	7	4.2	70.5	4.7	58.9	5.2	43.5
50	6.4	8	4.8	80.6	5.3	66.8	6.0	50.1
60	7.6	10	6.0	100.7	6.7	83.6	7.5	62.7
70	8.9	12	7.2	120.9	8.0	100.2	9.0	75.2
80	10.2	13	7.8	131.0	8.7	109.0	9.7	81.1
90	11.5	15	9.0	151.1	10.0	125.3	11.2	94.1
100	12.7	16	9.6	161.1	10.7	134.0	12.0	100.3
125	16.0	21	12.6	211.6	14.0	175.4	15.7	131.2
150	19.1	25						

Table B5
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in Low Permeability Soils (Clays). Rod Diameter = 2 in. (5.1 cm)

	Volume, gal		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
Depth, ft	Open Hole	Estimated Grout Needed	Water, gal	Cement, lb	Water, gal	Cement, lb	Water, gal	Cement, lb
5	0.8	1	0.6	10.0	0.7	8.7	0.7	5.8
10	1.6	2	1.2	20.1	1.3	16.3	1.5	12.5
15	2.4	3	1.8	30.2	2.0	25.1	2.2	18.4
20	3.3	4	2.4	40.3	2.7	33.8	3.0	25.0
25	4.1	5	3.0	50.4	3.3	41.3	3.7	30.9
30	4.9	6	3.6	60.4	4.0	50.1	4.5	37.6
35	5.7	6	3.6	60.4	4.0	50.1	4.5	37.6
40	6.5	7	4.2	70.5	4.7	58.9	5.2	43.5
50	8.2	9	5.4	90.7	6.0	75.2	6.7	56.0
60	9.8	11	6.6	110.8	7.3	91.5	8.2	68.5
70	11.4	12	7.2	120.9	8.0	100.2	9.0	75.2
80	13.1	14	8.4	141.0	9.3	116.5	10.5	87.8
90	14.7	16	9.6	161.2	10.7	134.1	12.0	100.3
100	16.3	18	10.7	180.0	12.0	150.4	13.5	112.9
125	20.4	22	13.1	220.0	14.7	184.2	16.5	138.0
150	24.5	27	16.1	270.3	18.0	225.5	20.2	168.9

Table B6

Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in High Permeability Soils (Sands). Rod Diameter = 2 in. (5.1 cm)

Depth, ft	Volume, gal		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, gal	Cement, lb	Water, gal	Cement, lb	Water, gal	Cement, lb
5	0.8	1	0.6	10.0	0.7	8.7	0.7	5.8
10	1.6	2	1.2	20.1	1.3	16.3	1.5	12.5
15	2.4	3	1.8	30.2	2.0	25.1	2.2	18.8
20	3.3	4	2.4	40.3	2.7	33.8	3.0	25.1
25	4.1	5	3.0	50.4	3.3	41.3	3.7	31.0
30	4.9	6	3.6	60.4	4.0	50.1	4.5	37.6
35	5.7	7	4.2	70.5	4.7	58.9	5.2	43.5
40	6.5	9	5.4	91.0	6.0	75.2	6.7	56.0
50	8.2	11	6.6	110.8	7.3	91.8	8.2	69.0
60	9.8	13	7.8	131.0	8.7	109.0	9.7	81.1
70	11.4	15	9.0	151.1	10.0	125.3	11.2	94.1
80	13.1	17	10.2	171.3	11.3	142.0	12.7	106.6
90	14.7	19	11.4	191.4	12.7	158.7	14.2	119.1
100	16.3	21	12.6	211.6	14.0	175.4	15.7	131.2
125	20.4	26	15.5	260.2	17.3	216.8	19.5	163.0
150	24.5	32	19.1	320.6	21.3	267.0	24.0	200.6

Table B7

Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in Low Permeability Soils (Clays). Rod Diameter = 1-3/8 in. (3.5 cm)

Depth, meters	Volume, liters		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg
1	1	1	1	2	1	1.5	1	1
2	1.9	2	1.2	2.4	1.3	2.0	1.5	1.5
4	3.8	4	2.4	4.8	2.7	4.0	3.0	3.0
6	5.8	6	3.6	7.2	4.0	6.0	4.5	4.5
10	9.6	11	6.6	13.2	7.3	11.0	8.2	8.2
12	11.5	13	7.8	15.6	8.7	13.0	9.7	9.7
14	13.5	15	9.0	18.0	10.0	15.0	11.2	11.2
16	15.4	17	10.2	20.4	11.3	17.0	12.7	12.7
18	17.3	19	11.4	22.8	12.7	19.0	14.2	14.2
20	19.2	21	12.6	25.2	14.0	21.0	15.7	15.7
25	24	26	15.6	31.2	17.3	26.0	19.5	19.5
30	28.9	32	19.2	38.4	21.3	32.0	24.0	24.0
35	33.7	37	22.2	44.4	24.7	37.0	27.7	27.7
40	38.5	42	25.1	50.2	28.0	42.0	31.5	31.5
45	43.3	48	28.7	57.4	32.0	48.0	36.0	36.0

Table B8

Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in High Permeability Soils (Sands). Rod Diameter = 1-3/8 in. (3.5 cm)

Depth, meters	Volume, liters		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg
1	1.0	1	1	2	1	1.5	1	1
2	1.9	2	1.2	2.4	1.3	2.0	1.5	1.5
4	3.8	5	3.0	6.0	3.3	5.0	3.7	3.7
6	5.8	8	4.8	9.6	5.3	8.0	6.0	6.0
10	9.6	12	7.2	14.4	8.0	12.0	9.0	9.0
12	11.5	15	9.0	18.0	10.0	15.0	11.2	11.2
14	13.5	18	10.8	21.6	12.0	18.0	13.5	13.5
16	15.4	20	12.0	24.0	13.3	20.0	15.0	15.0
18	17.3	22	13.2	26.4	14.6	22.0	16.5	16.5
20	19.2	25	15.0	30.0	16.7	25.0	18.7	18.7
25	24.0	31	18.5	37.0	20.6	31.0	23.2	23.2
30	28.9	38	22.8	45.6	25.3	38.0	28.5	28.5
35	33.7	44	26.3	52.7	29.3	44.0	33.0	33.0
40	38.5	50	30.0	60.0	33.3	50.0	37.5	37.5
45	43.3	56	33.5	67.0	37.3	56.0	42.0	42.0

Table B9
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in Low Permeability Soils (Clays). Rod Diameter = 1-3/4 in. (4.4 cm)

Depth, meters	Volume, liters		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg
1	1.5	2	1.2	2.4	1.3	2.0	1.5	1.5
2	3.0	3	1.8	3.6	2.0	3.0	2.2	2.2
4	6.1	7	4.2	8.4	4.7	7.0	5.2	5.2
6	9.1	10	6.0	12.0	6.7	10.0	7.5	7.5
10	15.2	17	10.2	20.4	11.3	17.0	12.7	12.7
12	18.2	20	12.0	24.0	13.3	20.0	15.0	15.0
14	21.3	24	14.4	28.8	16.0	24.0	18.0	18.0
16	24.3	27	16.2	32.4	18.0	27.0	20.2	20.2
18	27.4	30	18.0	36.0	20.0	30.0	22.5	22.5
20	30.4	34	20.3	40.6	22.7	34.0	25.5	25.5
25	38	42	25.1	50.2	28.0	42.0	31.5	31.5
30	45.6	50	30.0	60.0	33.3	50.0	37.5	37.5
35	53.2	59	35.3	70.6	39.3	59.0	44.2	44.2
40	60.1	67	40.1	80.2	44.7	67.0	50.2	50.2
45	68.4	75	45.0	90.0	50.0	75.0	56.2	56.2

Table B10
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in High Permeability Soils (Sands). Rod Diameter = 1-3/4 in. (4.4 cm)

	Volume, liters		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
Depth, meters	Open Hole	Estimated Grout Needed	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg
1	1.5	2	1.2	2.4	1.3	2.0	1.5	1.5
2	3.0	4	2.4	4.8	2.7	4.1	3.0	3.0
4	6.1	8	4.8	9.6	5.3	8.0	6.0	6.0
6	9.1	12	7.2	14.4	8.0	12.0	9.0	9.0
10	15.2	20	12.0	24.0	13.3	20.0	15.0	15.0
12	18.2	24	14.4	28.8	16.0	24.0	18.0	18.0
14	21.3	28	16.8	33.6	18.7	28.0	21.0	21.0
16	24.3	32	19.2	38.4	21.3	32.0	24.0	24.0
18	27.4	36	21.5	43.0	24.0	36.0	27.0	27.0
20	30.4	39	23.3	46.6	26.0	39.0	29.2	29.2
25	38.0	49	29.3	58.6	32.7	49.0	36.7	36.7
30	45.6	59	35.3	70.6	39.3	59.0	44.2	44.2
35	53.2	69	41.3	82.6	46.0	69.0	51.7	51.7
40	60.8	79	47.2	94.4	52.6	78.9	59.2	59.2
45	68.4	89	53.2	106.4	59.3	89.0	66.7	66.7

Table B11
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in Low Permeability Soils (Clays). Rod Diameter = 2 in. (5.1 cm)

Depth, meters	Volume, liters		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg	Water, ℓ	Cement, kg
1	2	2	1.2	2.4	1.3	2.0	1.5	1.5
2	4.1	5	3.0	6.0	3.3	5.0	3.7	3.7
4	8.2	9	5.4	10.8	6.0	9.0	6.7	6.7
6	12.2	13	7.8	15.6	8.7	13.0	9.7	9.7
10	20.4	22	13.2	26.4	14.6	22.0	16.5	16.5
12	24.5	27	16.1	32.2	18.0	27.0	20.2	20.2
14	28.6	31	18.5	37.0	20.6	31.0	23.2	23.2
16	32.6	36	21.5	43.0	24.0	36.0	27.0	27.0
18	36.7	40	23.9	47.8	26.6	40.0	30.0	30.0
20	40.8	45	26.9	53.8	30.0	45.0	33.7	33.7
25	51.0	56	33.5	67.0	37.3	56.0	42.0	42.0
30	61.2	67	40.0	80.0	44.6	67.0	50.2	50.2
35	71.4	79	47.2	94.4	52.6	78.9	59.2	59.2
40	81.6	90	53.8	107.6	60.0	90.0	67.5	67.5
45	91.8	101	60.3	120.6	64.0	96.0	78.0	78.0

Table B12
Grout Mixtures Based on Estimated Grout to Fill Penetrometer Holes in High Permeability Soils (Sands). Rod Diameter = 2 in. (5.1 cm)

Depth, meters	Volume, liters		Water: Cement Ratios (Volume Basis)					
			0.75:1		1:1		1.5:1	
	Open Hole	Estimated Grout Needed	Water, l	Cement, kg	Water, l	Cement, kg	Water, l	Cement, kg
1	2.0	3	1.8	3.6	2,0	3.0	2.2	2.2
2	4.1	5	3.0	6.0	3.3	5.0	3.7	3.7
4	8.2	11	6.6	13.2	7.3	11.0	8.2	8.2
6	12.2	16	9.6	19.2	10.7	16.1	12.0	12.0
10	20.4	27	16.1	32.2	18.0	27.0	20.2	20.2
12	24.5	32	19.2	38.4	21.3	32.0	24.0	24.0
14	28.6	37	22.2	44.4	24.7	37.0	27.7	27.7
16	32.6	42	25.1	50.2	28.0	42.0	31.5	31.5
18	36.7	48	28.7	57.4	32.0	48.0	36.0	36.0
20	40.8	53	31.7	63.4	35.3	53.0	39.7	39.7
25	51.0	66	39.5	79.0	44.0	66.0	49.5	49.5
30	61.2	80	47.8	95.6	53.3	80.0	60.0	60.0
35	71.4	93	55.6	111.2	62.0	93.0	69.7	69.7
40	81.6	106	63.3	126.6	70.6	106.0	79.5	79.5
45	91.8	119	71.2	142.4	79.3	119.0	89.2	89.2

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Cone penetrometers are used in expedited site investigations to penetrate the subsurface for data collection or sampling efforts. Each penetration leaves a vertical conduit for potential contaminant transfer and is typically required to be sealed with an acceptable grouting material.

Several methods are used for sealing penetrometer holes. This research effort was undertaken to evaluate penetrometer rod retraction grouting through an expendable tip. Grout was injected at three different sites, allowed to cure in situ, and was then removed using a drill rig. The evaluation results indicated the adequacy of the grout seals, and specific recommendations are made for improvements in the current grouting system.

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